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SEDIMENT TRANSPORT IN SWISS TORRENTS

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ABSTRACT

Sediment loads have been measured in six Swiss mountain torrents over several decades. Most of these torrent catchments are situated in the prealpine belt. They have catchment areas of between 0·5 and 1·7 km^2. Bedslopes at the measuring sites vary between 5 and 17 per cent, and peak discharges up to 12 m^3 s^{-1} have been recorded. Geophone sensors installed in the Erlenbach stream allow bedload transport activity to be monitored and sediment volumes associated with each flood event to be determined. A detailed analysis of the measurements in this stream results in an empirical equation in which the sediment load per flood event is expressed as a function of the effective runoff volume (discharges above the threshold for bedload motion) and of the normalized peak discharge. For the total of 143 investigated flood events in the Erlenbach stream, the deviation of the predicted from the measured value is within a factor of two for more than two-thirds of all events. A distinction can be made between summer and winter events in analysing the bedload transport events. The summer events, mainly caused by thunderstorms, transport comparatively larger sediment loads than the winter events.

For the other investigated streams, the periods of the deposited sediment volume surveys cover in general several flood events. An analysis is performed analogous to that for the Erlenbach stream. The sediment loads show a similar dependency on the two factors effective runoff volume and normalized peak discharge. However, the exponents of these factors in the power law expressions differ from stream to stream. A comparison of the investigated stream shows that some of the variation can be explained by considering the bedslope above the measuring site. The inclusion of a bedslope factor is in agreement with laboratory investigations on bedload transport. © 1997 by John Wiley & Sons, Ltd.

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INTRODUCTION

The steeper the stream gradient the more intense is the sediment transport. During heavy rainstorm events, significant hazard is caused by floods and sediment movement in rivers and torrents in Alpine regions. Debris flows are generally more disastrous than fluvial sediment transport in steep torrents. Understanding of the fluvial sediment transport processes is important with respect to hazard zoning on fans and with regard to related processes of debris flows.

The objective of this paper is to present results of continuous bedload measurements in a mountain catchment, and to compare sediment transport data in relation to flood parameters for several mountain streams in Switzerland. The torrents considered in this study all have average bedslopes above 10 per cent.

Many studies have been performed related to bedload transport in rivers and streams of limited bedslope (in general, less than a few per cent slope). In steep torrents with bedslopes above 5 per cent, however, only very few studies have been made. It can be assumed that similar sediment transport mechanisms apply in both cases, although the boundary conditions appear to be more complex in torrents. Within the context of sediment transport processes in torrents, particularly bedload transport in steep channels and also debris flows, summaries of research are given by Rickenmann (1990), Meunier (1991) and Sieben (1993). In the last two decades, sediment transport investigations in the laboratory have been extended to the slope range of mountain torrents, i.e. for bed slopes above approximately 5 per cent. Such investigations are reported, for example, by Mizuyama (1977), Smart and Jäggi (1983), Bathurst *et al*. (1987) and Rickenmann (1990, 1991). The general conclusion of these experiments is that the sediment transport relationships developed originally for flat

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bedslope conditions can also be applied for the steep slope range, with some adjustments of exponents and coefficients.

Only very few attempts have been made to investigate the relationship between the threshold discharge and initiation of bedload transport based on field data of steep streams (Bathurst, 1987; Bathurst *et al*., 1987). Furthermore, both the field data and the laboratory data are restricted to bed slopes of less than 10 per cent. There is a general lack of observations on critical flow conditions for initiation of bedload motion, and on bedload motion in nature, particularly for bed slopes above 10 per cent.

In natural torrents, the very wide grain size distribution has a significant influence on the bed morphology and on the local hydraulic conditions. The bed stability is largely influenced by step–pool or cascade–pool structure of the longitudinal profile of many steep mountain torrents. Descriptions related to streambed morphology are given, for example, by Whittaker (1987), Grant *et al*. (1990) and Schaelchli (1991).

A torrent is generally characterized as a steep and short stream in sometimes unstable geologic formations and showing a rapid rainfall runoff response. Its peak flows are the result of short, intensive rainstorms or prolonged storms of moderate intensities. Field observations in natural gravel-bed channels indicate that, once in motion, the bedload exhibits considerable spatial and temporal variability, and that no simple relationship exists between the prevailing flow conditions and the instantaneous bedload transport rate (Bänziger and Burch, 1990; Rickenmann, 1994). In mountain torrents, this variability may be mainly related to a limited sediment availability, to the very wide grain size distribution and to the very irregular streambed geometry. The pulsing nature of bedload transport has also been observed in other small streams (Hayward, 1980; Beschta, 1981; Reid *et al*., 1985; Tacconi and Billi, 1987).

EXPERIMENTAL CATCHMENTS AND MEASURING INSTALLATIONS

At the beginning of this century, the Swiss Federal Institute for Forest, Snow and Landscape Research (formerly called the Swiss Forest Research Institute) established two experimental hydrologic catchments in the Emmental region, situated in the prealpine belt. The two streams, Rappengraben and Sperbelgraben, were selected primarily in order to study the influence of the forest on the runoff behaviour. To maintain the stream gauging stations in operation, the sediment deposits at the sand traps immediately upstream of the gauging weirs had to be cleared out periodically. Information on the volumes of the trapped sediments is available for rather long observation periods. The main characteristics of the two streams are given in Table I. Characteristic grain sizes were determined by sieve analysis in the case of deposits in a sediment retention basin, and by transect number analysis (Fehr, 1987) in all other cases.

Figure 1. Location of six experimental hydrologic catchments in Switzerland with regular measurements on sediment volumes. The numbers refer to the catchments as follows: 1 = Erlenbach, 2 = Rappengraben, 3 = Sperbelgraben, 4 = Schwändlibach, 5 = Rotenbach, 6 = Melera

Table I. Characteristics of Swiss experimental hydrologic catchments with sediment measurements. The selection of the periods used in the analysis is based on the reliability of the sediment survey data

Characteristic	Rappengraben 1	Rappengraben 2	Sperbelgraben	Melera	Rotenbach	Schwändlibach	Erlenbach
Catchment area (km^2)	0·70	0·60	0·54	1·05	1·66	1·38	0·74
Elevation							
lowest (m a.m.s.l.)	985	996	911	962	1274	1217	1110
highest (m a.m.s.l.)	1256	1256	1203	1773	1630	1642	1655
Geology	Conglomerate	Conglomerate	Conglomerate	Crystalline	Flysch	Flysch	Flysch
Forest cover (%)	35	30	99	84	14	29	39
Mean annual precipitation (mm)	1570	1570	1590	2060	1840	(1840)	2300
Mean annual streamflow (mm)	1040	1040	840	1490	1620	870	1850
Drainage density (km/km^2)	11	11	16	11	14	19	27
Highest peak flow ($m^3 s^{-1}$)	2·2	2·6	1·2	8·0	18	8·5	12
With estimated return period (years)	30–40	50–80	20–30	80–100	40–50	40–50	60–80
Length of main steam (m)	1090	810	1190	1490	2020	1990	2350
Mean stream gradient (%)	18	23	22	49	15	20	18
Width above gauging station (m)	4·2	3·5	3·3	5·4	5·2	5·5	3·8
Bedslope above gauging station (%)	6	11	11	17	5	5	17
d_{90} of transported bed material (cm)	4	4	4	5	15	16	14
d_{50} of transported bed material (cm)	1–2	1–2	1–2	1–2	8	9	2–4
Critical discharge, Q_c ($m^3 s^{-1}$)	0·35	0·30	0·28	0·5	2·5	1·5	0·5
Periods of sediment data used	1903–27	1928–57	1903–54	1936–51	1955–58 1975–93	1953–58 1976–92	1982–93
Mean annual sediment yield (m^3)	58	77	42	162	138	69	603
Number of sediment surveys used	16	19	31	11	25	26	27
Number of floods (with $Q > Q_c$)	95	125	101	56	112	113	260
Sediment trap (ST) or sediment retention basin (SRB)	ST	ST	ST	SRB	SRB	SRB	SRB

Other experimental hydrologic catchments were established in the southern Alps (Melera) and in the Schwarzsee region (Rotenbach and Schwändlibach), situated in the prealpine belt in western Switzerland. Since about 1970, several hydrologic catchments have been instrumented in the Alptal in the Prealps of central Switzerland; the Erlenbach is one of these streams under observation. The main characteristics of these other streams are also given in Table I. For the total observation period of a given stream, some of the sediment surveys are of insufficient quality. In the analysis, only the reliable data have been used, corresponding to the selected periods indicated in Table I. The location of the catchments is shown on a map in Figure 1. The development of sediment transport investigations in small Swiss streams is summarized by Zeller (1985).

As most detailed observations on bedload transport are available for the Erlenbach stream, the hydrologic

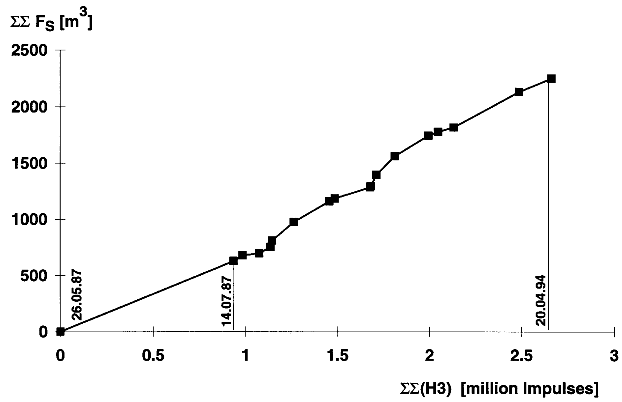

Figure 2. Erlenbach stream: cumulative sediment in the retention basin, $\Sigma\Sigma F_S$, against cumulative hydrophone impulses, ΣΣ(H3). In the first measuring period (26.5.1987–14.7.1987) the number of impulses was above average; this may be due to two flood events with high peak runoffs (Q_p of 3·5 and 3·0 $m^3 s^{-1}$)

characteristics of this catchment are described here in more detail. High intensity storms are frequent in the summer and cause sediment transport. Annual precipitation total are usually around 2300 mm per year, distinctly higher than the average value for Switzerland of 1500 mm. Snow usually falls from November through to April. About 30–40 per cent of the annual precipitation falls as snow. Midwinter thawing periods are frequent and interrupt the cold winter periods regularly. Snowpack is therefore very variable and may reach a maximum of up to 800 mm water equivalent one year, and a minimum of 100 mm the next (Keller, 1989).

In the Erlenbach, the snowmelt season in the spring may start in early March or as late as mid-April and a continuing elevated runoff during about one month is the rule. Rain-on-snow events occur almost every year. Relatively frequent high intensity rainfall events in summer cause sharp rises to peaks of short duration. The highest peak flow of 12 $m^3 s^{-1}$ in the Erlenbach was measured during the flood event of 25 July 1984. On this day the precipitation amounted to 120 mm, with a peak of 60 mm during one hour, which corresponds to a recurrence interval of 60–80 years. The total sediment load transported during this flood event was estimated at 2000 m^3.

Detailed information on the hydrologic characteristics of the other catchments are given by Engler (1919) and Burger (1934) for the Emmental region (Rappengraben and Sperbelgraben), by Burger (1945) for the Melera stream, and by Naegeli (1959) and Keller (1965) for the Schwarzsee region (Rotenbach and Schwändlibach).

BEDLOAD MEASUREMENTS IN THE ERLENBACH STREAM

In the Erlenbach stream, flood events with substantial bedload transport occur rather frequently: on the average there are about 20 events per year. As the side slopes of the channel are rather unstable, with creeping and sliding activities at many locations, there is a regular sediment supply to the streambed. Close to the confluence with the Alp river, a stream gauging station and a sediment retention basin with a capacity of about 2000 m^3 were built in 1983. Since October 1986 the bedload transport has been continuously monitored by a geophone measurement system (Bänziger and Burch, 1990, 1991; Burch, 1994). The bedload sensors, called hydrophones, are installed on the bottom of the inlet channel to the sediment retention basin. They record the signal induced by the impact of bedload grains transported over the measuring cross-section.

The total sediment discharge was determined 16 times during the period from May 1987 to April 1994 by surveying the sediment volume accumulated in the retention basin, F_S. Consequently, the sum of the hydrophone impulses was determined for the time spans corresponding to the observation periods of the

volume surveys. Figure 2 shows the cumulative sediment volume $\Sigma\Sigma F_S$ in relation to the cumulative hydrophone impulses registered by sensor H3, $\Sigma\Sigma$(H3). The gradient between each point on the graph gives the calibration factor. The calibration factors in the measuring period (14.7.87 to 20.4.94) fluctuate, but seem to average out in the long run. During the first measuring period (26.5.87 to 14.7.87) the number of impulses registered was above average; this is possibly due to two flood events having very high peak runoffs within the investigated period. In the further analysis, two conversion equations were applied to express the sediment load per flood event, F_E (in m^3), as a function of the number of hydrophone impulses:

$$F_E = \Sigma(\mathrm{H3})/1500 \text{ for the period (26.5.87 to 14.7.87)} \quad (1a)$$

$$F_E = \Sigma(\mathrm{H3})/1100 \text{ for the period (14.7.87 to 20.4.94)} \quad (1b)$$

where Σ(H3) is the number of hydrophone impulses recorded for each flood event. Only for a few single flood events could the sediment load be determined directly by a survey. If the conversion Equation 1 is applied for the whole period of observations, the sum of the F_E values and the sum of the F_S values deviate by less than 2 per cent.

While converting the data it must be borne in mind that not only gravel and fairly large stones (with diameters of more than 30 cm) are deposited in the retention basin, but also sand, silt and clay particles. The hydrophone sensors, however, register bumps only from the heavier grains transported as bedload and not from particles transported in suspension. It has been found that a sediment grain heavy enough to register an impulse must measure at least 1 cm (for higher flows the limiting grain size may be even larger). This limiting grain size has been determined by recording the passage of single grains of different sizes over the bedload sensor. Consequently, as a first approximation for the conversion of data it must be assumed that the proportions of bedload and suspended material remain constant in the intervals between flood events. Based on grain size analysis of the deposits in the retention basin, it has been found that about 50 per cent by volume of the material has a grain size larger than 1 cm. In comparison, the deposits of grains larger than 3 cm comprise about 30 per cent by volume of the total sediment deposit (Rickenmann and Dupasquier, 1994). It must also be borne in mind that during high floods, additional fine particles in suspension are transported through the basin as washload.

BEDLOAD TRANSPORT EVENTS IN THE ERLENBACH STREAM

In general, bedload transport begins at a certain threshold discharge and continues until another threshold discharge is reached during the recession part of the hydrograph. However, there are also events during which bedload transport at the measuring site ceases for a certain time, even though the flow rate is still increasing, and commences again on the rising or falling limb of the hydrograph.

Most of the flood events in the Erlenbach show a triangular shaped hydrograph. In order to distinguish between consecutive events, a single event is generally defined by a hydrograph composed of one rising and one falling limb. A distinction has been made between events occurring during the summer and those occurring under winter conditions. The latter category includes snowmelt runoff events and rain on snow events when at least half of the catchment area is covered by snow.

Characteristic mean values and idealized hydrographs are shown in Figure 3. For the period under consideration (1987–1994), 91 summer events and 51 winter events have been analyzed. For the summer events, the average duration of bedload transport is about 100 min. The average peak discharge, Q_p, is almost 1 m^3 s^{-1}, the threshold discharge at the beginning of transport, Q_c, is $0{\cdot}46$ m^3 s^{-1} and that at the end of transport, $Q_{c,e}$, is $0{\cdot}63$ m^3 s^{-1}. During the summer months, the sediment-carrying events in the Erlenbach are mainly caused by thunderstorms. If the sum of the hydrophone impulses is assumed to be indicative of the total sediment volume passing the measuring site, then only about 10 per cent of the total sediment is transported during winter conditions.

Looking at the critical discharge Q_c at the onset of bedload transport, a clear seasonal trend can also be observed (Figure 4). This threshold discharge tends to be smaller in winter than in summer. Further, the variability of the threshold discharge appears to be larger in summer than in winter. Q_c shows variation by a

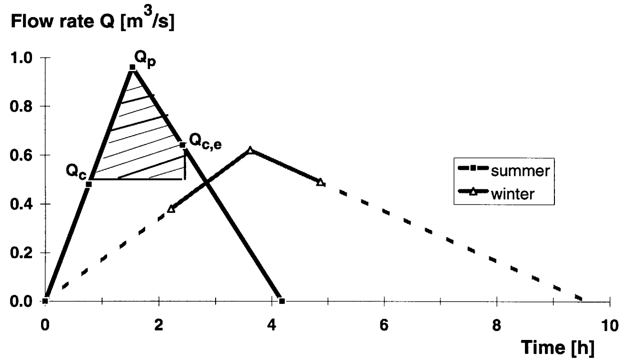

Figure 3. Erlenbach stream: idealized mean hydrographs of bedload transport events for summer and winter conditions. The shaded area corresponds to the effective runoff volume, V_{re}. (See text for explanation of charactistic values.)

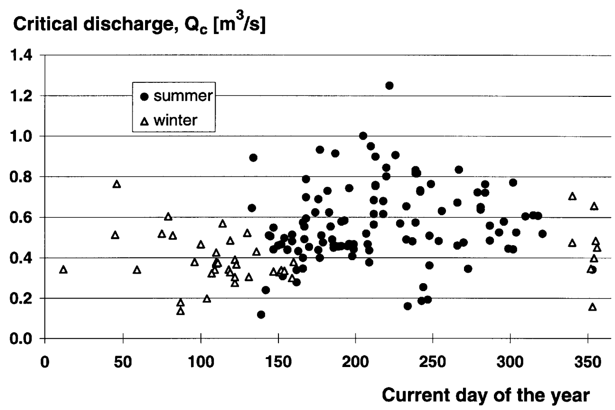

Figure 4. Erlenbach stream: threshold flow at the onset of bedload transport, Q_c, in relation to the current day of the year. The values of Q_c refer to grains in motion that are larger than about 1 cm

factor of about two around the mean value. During winter conditions the average value is smaller than in summer. A possible explanation could be that the soil is frozen so that the transported grains are mainly fines which have not been embedded. Another reason may be an increased supply of predominantly fine material to the channel by enhanced creeping of the sideslopes during the wet snowmelt season. A more limited grain size distribution available for transport during winter conditions could also account for the observed intermittent breaks with no transport activity during the same event (Rickenmann, 1994).

It should be noted that the values for the critical discharge, Q_c and $Q_{c,e}$, refer to grains in motion that are larger than about 1 cm, and therefore it is not a critical discharge for bedload movement in the strict sense. However, it can be assumed that a considerable part of the grains smaller than 1 cm are transported in suspension, and thus the measured value is a good approximation for the threshold discharge at initiation of bedload transport.

SEDIMENT LOAD AND FLOOD PARAMETERS

Although there seems to be no simple relation between flow rate and bedload transport intensity as expressed by the number of hydrophone impulses per minute (Bänziger and Burch, 1991), one may expect a clearer trend if the data are averaged over a longer period. If the sediment load per flood event, F_E, is considered, it is found to be dependent on the total runoff volume during each flood event, V_r. There is a (non-linear) relation between the two parameters although the scatter is large, the variation extending over more than one order of magnitude.

F_E displays a better correlation with the effective runoff volume relevant to the sediment transport, V_{re}, which is illustrated in Figure 5. Here, the effective runoff volume, V_{re}, was calculated by integrating the flow

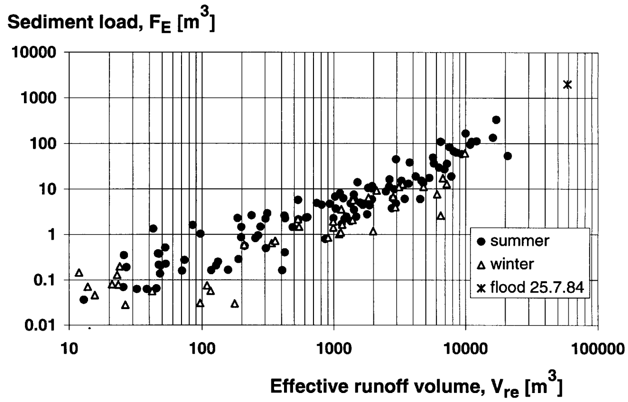

Figure 5. Analysis of flood events in the Erlenbach stream: sediment load, F_E, in relation to the effective runoff volume, V_{re}, above the threshold discharge for beginning of transport

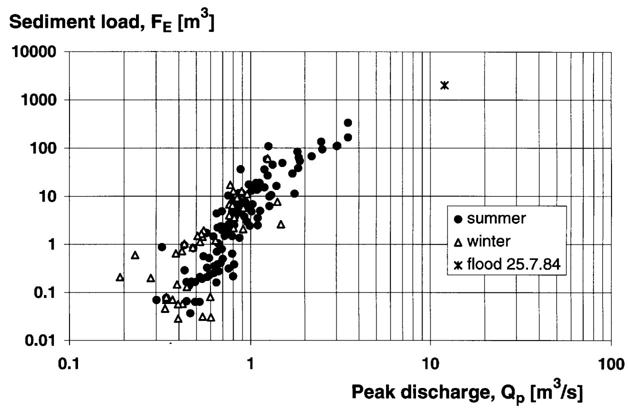

Figure 6. Erlenbach stream: sediment load per flood event, F_E, in relation to peak discharge, Q_p, during flood events

rate difference above the threshold discharge ($Q - Q_c$) for the time period with bedload activity for each event (V_{re} is represented by the shaded area in Figure 3). Considering summer conditions only, the data could be described best by two separate relationships. For larger effective runoff volumes (generally with $Q_p >> Q_c$), the correlation is better than for flow rates close to the threshold discharge (smaller effective runoff volumes).

Not surprisingly, the winter events show somewhat lower sums of hydrophone impulses for the same runoff volume, even though they have a smaller mean threshold discharge. It is possible that less sediment is available for transport during winter conditions, which are associated with temperatures generally below the freezing point. On the other hand, it may be expected that predominantly finer bed material is transported during such events.

A further observation included in Figure 5 is the largest flood event so far recorded in the Erlenbach torrent (25 July 1984). This event had a peak discharge of about $12\,m^3\,s^{-1}$ and transported $2000\,m^3$ of sediment into the retention basin. With an estimated recurrence interval of 60 to 80 years, it was much larger than any event during the hydrophone observation period.

Another influencing factor is the peak discharge, Q_p, of each flood event. Figure 6 shows that the F_E values also depend on the peak discharge. Interestingly, the maximum bedload transport intensity shows a similar dependence on the magnitude of Q_p: the maximum number of impulses per minute during an event appears to be some measure of the total sediment load. In both cases there is a bend in the dependence at a Q_p value of about $1\,m^3\,s^{-1}$, and the influence of Q_p above this threshold is smaller.

This sharp bend may be related to the range of fluctuation of the threshold discharge between 0·4 and $0{\cdot}8\,m^3\,s^{-1}$ (for flood events in summer; Figure 4). It is assumed that within this range a large part of sediment grain sizes

are set in motion, considering the sizes which are transported at all during flood events. Consequently, up to a discharge of about 1 $m^3\,s^{-1}$ the proportion of bed material grains in motion, contributing to the total sediment transport, increases rapidly. When the discharge exceeds this level, still larger sediment grains may be set in motion but may not contribute so much to the total sediment volume.

EMPIRICAL FORMULAE FOR SEDIMENT LOADS

As stated above, the sediment load per flood event, F_E, depends on the effective runoff volume, V_{re}, and on the peak discharge, Q_p. A regression computation for F_E using these parameters for 143 flood events, including the extreme event of July 1984, gives the following equation:

$$F_E = 0{\cdot}0114\,(V_{re})^{0{\cdot}72}(Q_p/Q_c)^{1{\cdot}50} \tag{2}$$

Both V_{re} and F_E are in cubic metres. Comparison of the computed and measured data gives the following statistical parameters: the correlation coefficient r is 0·94 and the standard error s_e is 93 per cent. In the regression computation the peak runoff, Q_p, has been normalized with a constant mean value for threshold discharge of $Q_c = 0{\cdot}5\,m^3\,s^{-1}$.

Through using logarithmic values, all data points were equally weighted. From a practical viewpoint, however, it is more important to have a reliable estimation of sediment transport during the more severe flood events. According to Equation 2, the extreme flood event of 1984 is overestimated by a factor of 1·8. Therefore the regression was recalculated for only those events whose Q_p exceeded 1 $m^3\,s^{-1}$ (49 events). The selection of this value is connected with the bend in the graph of F_E against Q_p at about 1 $m^3\,s^{-1}$ (Figure 6). A slight bend can also be seen in the curve of F_E plotted against V_{re} at a V_{re} value of about 1000 m^3 (Figure 5). Furthermore, it was found that the exponent of V_{re} may be set at 1·0 without significantly altering the correlation. Thus it was possible to formulate the following equation:

$$F_E = 0{\cdot}0021\,(V_{re})\,(Q_p/Q_c)^{0{\cdot}84} \tag{3}$$

Comparison of the computed and measured sediment transport reveals the following statistical parameters: the correlation coefficient r for all 143 events is 0·91 and the standard error, s_e, is 121 per cent. For the larger flood events, Equation 3 shows a better agreement between the computed and measured data than Equation 2. A further advantage of Equation 3 is that it is fully dimensionally balanced, i.e. it does not contain a dimensional constant. Figure 7 shows the predicted sediment loads, F_{Ep}, plotted against the measured sediment loads, F_E, by using Equation 3. For more than two-thirds of the events, the deviation of the computed value F_{Ep} lies within a factor of two of the measured value F_E.

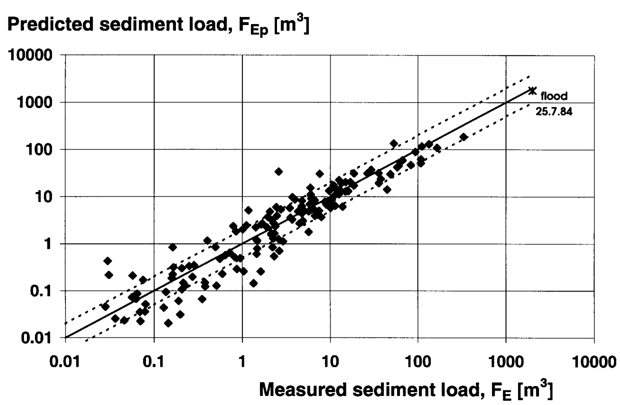

Figure 7. Erlenbach stream: computed sediment loads per flood event, F_{Ep} (with Equation 3), against measured sediment loads, F_E (determined according to the calibration relationship based on the hydrophone measurements). The deviations within the dotted lines are smaller than a factor of two

SEDIMENT MEASUREMENTS IN OTHER SWISS STREAMS

Data on transported total sediment or bedload volumes are also available for other Swiss streams, namely for the Rappengraben, Sperbelgraben, Melera, Rotenbach and Schwändlibach, as indicated in Table I. In these cases, surveys of the bedload traps were performed once per year or even less during certain periods. As can be inferred from Table I, there were on average about three to six flood events which contributed sediment to the trap or retention basin during each period between two successive surveys.

Based on laboratory investigations on sediment transport in steep channels (Rickenmann, 1990), an equation of the following type has been developed to describe the bedload transport rate, Q_B:

$$Q_B = AS^{\gamma}(Q - Q_c)^{\alpha} \tag{4}$$

where A is a constant, S is the bedslope, the exponent α has been set to 1, and γ has been found to vary between 1·5 and 2, depending on the slope range under consideration (Rickenmann, 1990, 1991). Integration of Equation 4 over the time of a flood event yields:

$$G_E = AS^{\gamma}V_{re}^{\alpha} \tag{5}$$

where G_E is the total bedload volume per flood event. Neglecting, for a given stream, the slope factor in Equation 5, it is in fact quite similar to Equations 2 and 3, which can be given in a general form as:

$$F_E = BV_{re}^{\alpha}(Q_p/Q_c)^{\beta} \tag{6}$$

where the values of the constant B and of the exponents α and β are to be determined empirically. For the streams under consideration, no information on bedload volumes is available for single flood events (apart from the Erlenbach stream). Looking at the periods between two consecutive surveys of the sediment deposits, Equation 6 can be expressed as:

$$\Sigma F_E = B\Sigma[V_{re}^{\alpha}(Q_p/Q_c)^{\beta}] \tag{7}$$

For the streams in Table I, including the Erlenbach stream, a regression analysis has been performed using the approach given by Equation 7 to find the best values of exponents α and β for predicting the total bedload volumes (measured at each survey). The result of these regression calculations is shown in Table II.

Table II. Best combinations of exponents α and β resulting from regression calculations using Equation 7. r denotes the correlation coefficient

Rappengraben 1				Sperbelgraben				Rotenbach				Erlenbach (82–93)			
α	β	$\alpha+\beta$	r^2	α	β	$\alpha+\beta$	r^2	α	β	$\alpha+\beta$	r^2	α	β	$\alpha+\beta$	r^2
0·3	0·1	0·4	0·86	0·2	0·3	0·5	0·86	0·4	1·5	1·9	0·80	1·2	0·6	1·8	0·97
0·3	0·2	0·5	0·86	0·2	0·4	0·6	0·86	0·4	1·3	1·7	0·79	1·0	0·9	1·9	0·97
0·3	0·4	0·7	0·85	0·3	0·5	0·8	0·86	0·6	1·0	1·6	0·78	0·9	0·9	1·8	0·96
0·4	0·5	0·9	0·84	0·4	0·5	0·9	0·84	0·7	0·8	1·5	0·78	0·9	0·7	1·6	0·96
0·5	0·5	1·0	0·84	0·4	0·4	0·8	0·84	0·7	1·0	1·7	0·77	0·8	1·0	1·8	0·95

Rappengraben 2				Melera				Schwändlibach				Erlenbach (87–93; July 84)			
α	β	$\alpha+\beta$	r^2	α	β	$\alpha+\beta$	r^2	α	β	$\alpha+\beta$	r^2	α	β	$\alpha+\beta$	r^2
0·4	0·5	0·9	0·57	0·1	1·7	1·8	0·96	0·4	2·5	2·9	0·65	1·0	0·8	1·8	0·98
0·3	0·5	0·8	0·57	0·1	1·6	1·7	0·95	0·4	2·0	2·4	0·64	0·8	1·0	1·8	0·97
0·3	0·4	0·7	0·56	0·2	1·7	1·9	0·94	0·7	2·0	2·7	0·63	0·7	1·5	2·2	0·96
0·5	0·4	0·9	0·56	0·3	1·6	1·9	0·93	0·7	2·5	3·2	0·61	0·4	1·5	1·9	0·94
0·5	0·5	1·0	0·56	0·4	1·6	2·0	0·90	1·0	2·0	3·0	0·60	0·8	0·8	1·6	0·92

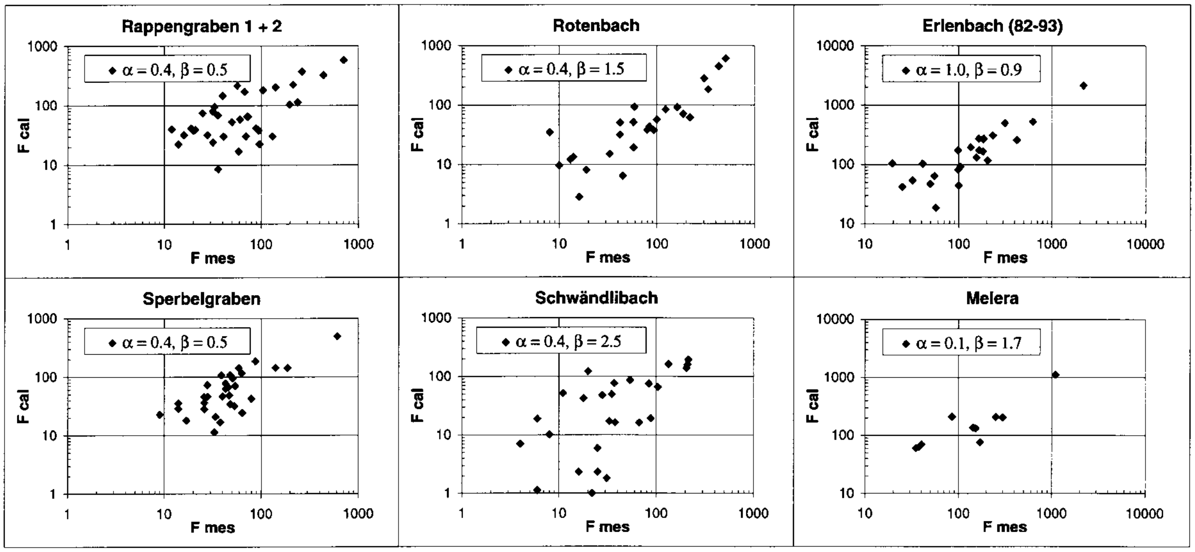

Figure 8. Comparison between calculated and measured sediment loads for Swiss torrents, for selected combinations of the exponents α and β. Both calculated (*F*cal) and measured (*F*mes) sediment loads are in cubic metres

A comparison between calculated and measured values of ΣF_E is given in Figure 8 for some examples. As illustrated in Figure 8, the scatter of the data points is generally larger for smaller values of bedload volumes (ΣF_E) and of streamflow intensity ($V_{re}^{\alpha}(Q_p/Q_c)^{\beta}$). This finding is in agreement with the analysis of sediment transport data from flume investigations, where the largest scatter between measured and predicted transport rates is observed for flow conditions close to those at initiation of bedload motion (Rickenmann, 1990).

It is noted that for the Erlenbach stream the analysis has been performed for two cases: (i) for the whole period of sediment surveys (1982–1993), and (ii) for the same data as analysed in the first part of the paper (1987–1993, plus the flood event of July 1984). It can be seen from Table II that the results for the second case are rather similar to those obtained in the analysis based on the hydrophone measurements to distribute the sediment loads to the flood events (cf. Equations 2 and 3).

For most of the investigated flood events, the hydrograph can be approximated by a triangular shape. It is obvious in this case that the factors in square brackets in Equation 7 are not independent, since the effective runoff volume V_{re} can be expressed as a function of the peak discharge Q_p, the critical discharge Q_c, and the time of the flood duration. Therefore it is not surprising that for the best regression equations, the sum of the two exponents, $\alpha+\beta$, varies only within a limited range. The corresponding regression coefficients (r^2) and the range of the 'best' combinations of the two exponents are shown in Table II.

Nevertheless, the analysis of the Erlenbach data in the first part suggests that it is meaningful to use both factors, V_{re} and Q_p/Q_c, to estimate sediment loads, for the magnitude of the peak flow is an indication of the flow strength. Further, the sediment availability seems to increase with increasing flow strength, at least for flow conditions which are not too far from (say up to about five times higher than) the critical conditions at initiation of bedload motion.

Double-mass plots have been prepared in order to make a comparison between bedload transport in the different streams. In Figure 9, the cumulative bedload, $\Sigma\Sigma G_E$, is shown as a function of the cumulative effective runoff volume, $\Sigma\Sigma V_{re}$. Here, ΣG_E refers to the volume of bedload sediment; in the cases with a sediment retention basin (Melera, Rotenbach, Schwändlibach, Erlenbach, see Table I) the bedload volume is estimated to be half of the total deposited sediment volume. This ratio of 50 per cent bedload is based on a grain size analysis at different locations in the sediment retention basin of the Erlenbach stream (where 50 per cent of the deposit consists of grains larger than about 1 cm).

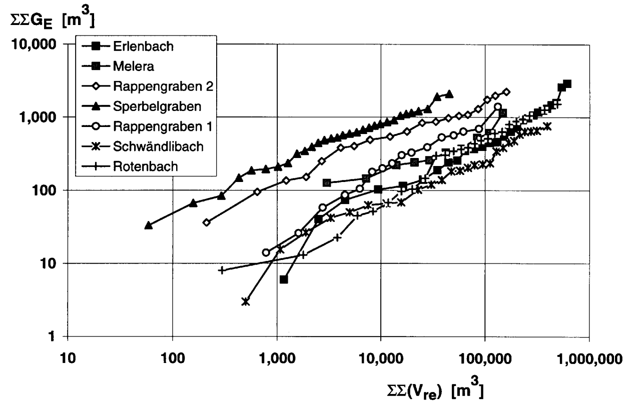

Figure 9. Cumulative bedload, $\Sigma\Sigma G_E$, as a function of the cumulative effective runoff volume, $\Sigma\Sigma V_{re}$. The data have been ordered according to increasing values of ΣV_{re}

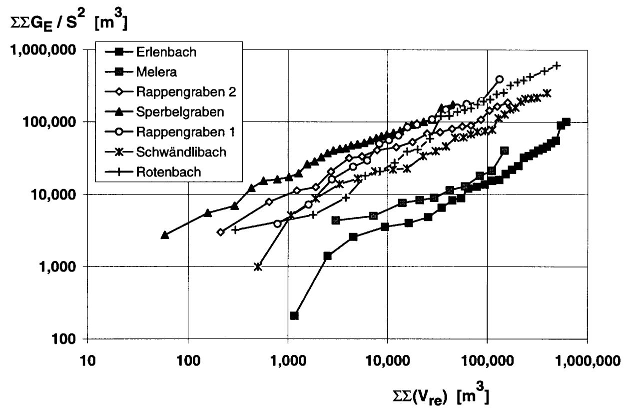

Figure 10. Cumulative bedload, $\Sigma\Sigma G_E$, divided by the bedslope factor S^2 (upstream of the measuring site), shown as a function of the cumulative effective runoff volume, $\Sigma\Sigma V_{re}$. The data have been ordered according to increasing values of ΣV_{re}

The data in Figure 9 have been ordered according to increasing values of ΣV_{re} (effective runoff volume between two sediment surveys). In this way a more systematic comparison can be made, since the plotting position is less influenced by the more infrequent and random occurrence of high intensity events. In order to account for the slope influence on bedload transport, the $\Sigma\Sigma G_E$ values were divided by the factor S^2, and the respective double-mass curves are shown in Figure 10. An average bedslope value over a 50 to 100 m reach upstream of the gauging station has been used. Here, the slope exponent in Equation 4 or 5 has been set as $\gamma = 2$, since this value has been found in laboratory investigations to apply best for channel slopes above about 3 per cent (Rickenmann, 1990).

As can be seen from Table II, the sum of the exponents α and β of the two runoff parameters is in the range between 1 and 2 for the optimum average correlation of all investigated streams. Therefore, similar diagrams to those in Figures 9 and 10 have been prepared by using abscissa values of $\Sigma\Sigma\,[V_{re}\,(Q_p/Q_c)]$ in Figures 11 and 12. This representation allows a comparison to be made among the different streams by assuming a stronger influence of the runoff parameters (i.e. with $\alpha + \beta = 2$) on bedload volumes.

Looking at both pairs of figures, 9/10 and 11/12, it is interesting to note that the curves representing the streams plot generally closer together if the slope factor S^2 is included. An exception are the data of the Erlenbach and the Melera streams. These streams have the highest bedslope (17 per cent) above the measuring site (see Table I). The Erlenbach streambed shows a pronounced cascade–pool structure, where the cascades account for about half of the total elevation drop. This implies that the mean energy slope available for sediment

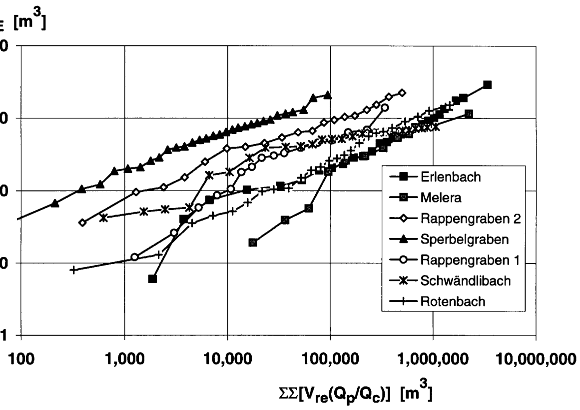

Figure 11. Cumulative bedload, $\Sigma\Sigma G_E$, as a function of the cumulative effective runoff volume times a peak flow factor, $\Sigma\Sigma[V_{re}(Q_p/Q_c)]$. The data have been ordered according to increasing values of $\Sigma[V_{re}(Q_p/Q_c)]$

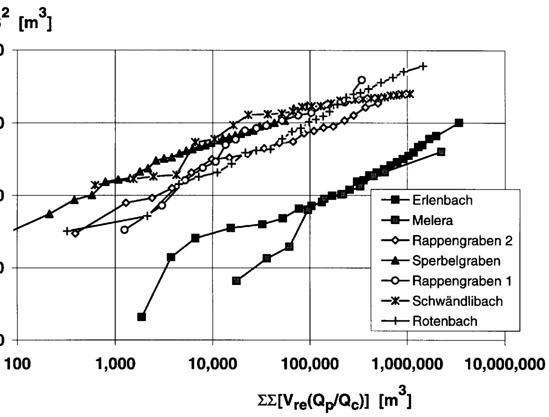

Figure 12. Cumulative bedload, $\Sigma\Sigma G_E$, divided by the bedslope S^2 above the measuring site, shown as a function of the cumulative effective runoff volume times a peak flow factor, $\Sigma\Sigma[V_{re}(Q_p/Q_c)]$. The data have been ordered according to increasing values of $\Sigma[V_{re}(Q_p/Q_c)]$

transport is considerably smaller than the average bedslope value including the cascades. If a bedslope of about 8 per cent were used for the Erlenbach stream, neglecting the cascades, the curves of the Erlenbach in Figures 10 and 12 would plot closer to the other data. A similar argument also applies to the Melera, where bedrock cascades exist immediately upstream of the measuring site.

DISCUSSION

Bedload transport observations in Turkey Brook, England, yield considerably larger threshold values for the beginning of bedload transport than for the cessation of bedload transport. This difference is explained by the interlocking of particles, hiding of grains, and static and dynamic friction angles (Reid *et al.*, 1985). For the Erlenbach stream, the generally higher threshold value at the end of transport is thought to be due mainly to the limited availability of movable sediment in the channel bed. It is likely that the sediment storage zones of smaller particles are emptied towards the end of the flood event, requiring higher discharges to move the coarser grains still available for transport. Looking at the relationship between bedload transport and water discharge, there is a trend for higher transport intensities on the rising limb of the hydrograph than on the falling limb; however, there is generally not a simple hysteretic loop for single flood events (Rickenmann, 1994).

It is interesting to note that a similar pattern to that shown in Figure 5 has also been found for other streams. For Turkey Brook, with a bedslope of 0·86 per cent at the measuring site, the flood average bedload discharge

has been shown to correlate with the average stream power in excess of the traction threshold (Reid and Frostick, 1986). Equation 4 is a general version of the well known Schoklitsch equation (Schoklitsch, 1962) which can be given in the form:

$$Q_B = CS^{1\cdot 5}(Q - Q_c) \tag{8}$$

where C depends on the solid to fluid density ratio. Bathurst *et al*. (1987) have used bedload transport data from nine gravel-bed streams with bedslopes up to 4 per cent and found general agreement with the Schoklitsch equation.

It is therefore also confirmed from other studies that a general relationship exists between bedload discharge, water discharge and the bedslope. It is noted that different exponents γ at the slope factor (Equation 4) have been proposed. In the present study, the analysis referring to Figures 10 and 12 has also been performed using slope exponents $\gamma = 1\cdot 5$ and $\gamma = 1$, but the best agreement has been found for a value $\gamma = 2$, a finding that is also supported by laboratory data (Rickenmann, 1991).

Considering Table II, it is interesting to note that some groups of streams can be distinguished according to lithology of the streambed material. The streams with conglomerate material have similar ‘best’ exponents, with sums between about 0·5 and 1; these are the Sperbelgraben and Rappengraben, and also another Swiss stream in conglomerate material (Rietholzbach) not presented here. On the other hand, the streams in flysch and crystalline bed material (Erlenbach, Rotenbach and Melera) have higher ‘best’ exponents between about 1·5 and 2, apart from the Schwändlibach. The Schwändlibach shows the largest scatter between calculated and measured sediment loads, which may possibly indicate that the data are less reliable than for the other streams. Another distinction is observed in Figure 10 and partly in Figure 12, where the data from streams in conglomerate material (Sperbelgraben and Rappengraben) tend to have higher transport intensities than the other streams. This may be due to the more rounded form of the particles, which facilitates transport.

CONCLUSIONS

Sediment transport data are available for several Swiss streams in the prealpine region. These streams have catchment areas of between 0·5 and 1·7 km^2, mean stream gradients between 15 and 49 per cent, and bedslopes above the measuring site between 5 and 17 per cent. In most of these streams, sediment volumes transported by flood events have been monitored over several decades.

The most detailed observations are made in the Erlenbach stream. There, geophone sensors allow the measurement of bedload transport intensities and thus it is possible to determine sediment volumes for each single flood event (F_E). The analysis of about 140 events shows that the F_E values can be expressed reasonably well as a function of the effective runoff volume (V_{re}) and the normalized peak discharge (Q_p/Q_c).

A similar empirical analysis has been performed for the other Swiss streams, for which the transported sediment load surveys cover longer periods that include several flood events. It could be confirmed that a generally similar dependency also exists in these cases, although the relative importance of the two flood parameters varies somewhat from stream to stream. Possibly, the exponents of the flood parameters in Equation 7 are related to the lithology of the streambed material. The analysis of the Erlenbach data suggests that the magnitude of the peak flow is to some extent a measure of the sediment availability.

It is observed that the scatter between predicted and measured sediment loads is smaller, in general, for flow conditions clearly above the critical discharge. This finding is in agreement with the results of flume studies, which show the difficulty of predicting bedload transport rates at discharges close to critical conditions at the beginning of grain movement.

A comparison of the data from all investigated streams indicates that the inclusion of a slope factor may explain some of the difference in the transported sediment volumes for a given combination of flow parameters. This finding is in agreement with the analysis of bedload transport measurements in laboratory flumes with similar channel gradients. It is also confirmed by other studies, including field data from gravel-bed streams with bedslopes up to 4 per cent.

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